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THESIS

SCHEDULING TESTS ON THE NAVAL WEAPONS CENTER RANGE FACILITIES

by

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The Naval Weapons Center (NWC) is the Navy's primary research, development, test and evaluation facility for air-launced weapons. As such, its many ranges and associated equipment and personnel are used extensively for the testing of weapons systems. The Scheduling Office within the NWC Range Department is responsible for determining which tests are conducted during each week. Since there are more test requests than time or facilities, the Scheduling Office struggles, by hand, to schedule as many tests as possible. This thesis develops and implements an integer programming model designed to maximize the sum of priorities for tests scheduled within a weekly master schedule. The X-System was used sequentially to solve five daily schedules to produce a weekly master schedule while insuring sufficient resources are available to conduct the tests. (continued)

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Scheduling Tests on the Naval Weapons Center Range Facilities

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ABSTRACT

The Naval Weapons Center (NWC) is the Navy's primary research, development, test and evaluation facility for air-launched weapons. As such, its many ranges and associated equipment and personnel are used extensively for the testing of weapons systems. The Scheduling Office within the NWC Range Department is responsible for determining which tests are conducted during each week. Since there are more test requests than time or facilities, the Scheduling Office struggles, by hand,to schedule as many tests as possible. This thesis develops and implements an integer programming model designed to maximize the sum of priorities for tests scheduled within a weekly master schedule. The X-System was used sequentially to solve five daily schedules to produce a weekly master schedule while insuring sufficient resources are available to conduct the tests.

The model selected a set of tests and their test times from a pool of fifty tests with 1440 potential schedules. Thirty-eight of the fifty tests were scheduled using approximately eight and a half minutes of CPU time on an IBM 3033AP. This is considerably faster than the current manual process which requires an entire day to create a weekly schedule.

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I. INTRODUCTION

A. WEAPONS TESTING

The Naval Weapons Center (NWC), located in the northern Mojave Desert is the Navy's primary research, development, test, and evaluation facility for air-launched weapons. As such, Center personnel are responsible for making sure that weapons systems can perform adequately under all possible conditions. As part of their efforts to provide combatants with the best weapons systems, extensive field testing of prototypes and production models is conducted at the Center. These tests vary from warhead detonations, to captive telemetry tests of sensor systems, to tests of live warhead rounds. These tests are critical to the evaluation of new and existing weapons systems.

Given the critical nature of these tests, and the fact that the Center is the only facility with a significant number of test ranges, range time is a scarce resource. The ability of the Center to run tests is further restricted by the limited support facilities such as radars, telemetry vans, lasers, and the personnel required to conduct the tests.

B. TEST SCHEDULING

The responsibility of managing the ranges at NWC falls primarily upon the Range Department. Within this department, the Scheduling Office and other organizations have control over more than thirty different range facilities. The majority of tests conducted on the ranges are scheduled through The Scheduling Office. It is this office which determines when tests are scheduled.

Currently, scheduling is performed by three people whose major responsibility is to generate and maintain the weekly schedule. This is done with little computerization other than the printing of a schedule once it has been developed. For the most part, the actual scheduling, resource juggling, and last minute changes are carried out every week using a large "chalk board". This effort requires weekly meetings with all the managers of the various support facilities or their representatives. These efforts are time-consuming and manpower- intensive.

Given the complex nature of the scheduling problem, schedulers work to achieve a feasible schedule which is consistent with Department of Defense (DOD) priorities. In addition, it is hoped that the schedule will be flexible enough to adapt to last minute modifications due to changes in resource availability, test plans, weather, etc.

C. THESIS OBJECTIVE

The goal of this thesis is to apply computer-aided scheduling techniques to the NWC Range scheduling efforts. This will be accomplished by using an integer programming model.

It is hoped that by using such techniques, schedulers at NWC will be able to improve the efficiency of the scheduling effort and, as a result, reduce the manpower requirements, increase the speed with which the schedules are generated, and allow for the scheduling process to be more flexible.

In addition, since computerization will allow schedulers to move beyond feasibility and to approach optimal decisions, this computerization should increase range productivity by decreasing "dead time" and provide a better response to Department of Defense priorities.

The analysis in this thesis draws upon work in the field of large-scale integer programming. The approach taken to the test-scheduling problem is similiar to other scheduling methodologies in which all candidate schedules are generated, and an optimal set of schedules is selected from among the candidates. Examples of similiar work include a tanker-scheduling problem investigated by Brown, Graves and Ronen [Ref. 1] and an air-cargo scheduling problem by Marsten, Mueller, and Killion [Ref. 2]. The test-scheduling problem is a generalization of set packing problems in that

both the constraint matrix and the right-hand side have general integer coefficients instead of just 1s. This formulation, at least with regard to the partitions dealing with range time, is also a generalization of workforce scheduling described, for example, in the staff covering problems in Schrage [Ref. 3] and the work done by Bartholdi, Orlin, and Ratliff [Ref. 4]. Ignoring its time dimension, the test scheduling problem also has the flavor of a capital budgeting model with side constraints, e.g. Weingartner [Ref. 5].

This thesis describes the mathematical programming method developed for solving the test-scheduling problem. Chapter II presents the basic test-scheduling problem. The development of the mathematical model is presented in Chapter III. Chapter IV describes the work required to implement the model. Finally, the last chapter, Chapter V, contains the results of the process and a critique of its effectiveness, and recommendations for further investigation.

II. THE TEST SCHEDULING PROBLEM

A. OBJECTIVE

The Scheduling Office is responsible for providing weapons programs with range time and test facilities in a timely fashion. Unfortunately, there are many more requests for test time than resources to support them. This means that the Scheduling Office must decide which tests to run, and when to run them. For each test request, the office must select a block of time for the test to be conducted and make sure that the people, equipment, and range facilities required to conduct the test are available. The goal of the Office is to schedule as many tests as possible within equipment, personnel and time constraints. In addition, the schedule of tests must also reflect the Department of Defense priorities established in Washington D.C.

The decisions as to which test to run, and when to run them are based upon two basic goals:

1) Schedule a week's worth of tests in such a way as to minimize the amount of time each range is idle.

2) Work to schedule those tests associated with high priority weapons programs. This implies insuring that certain tests are conducted during predetermined time windows.

With these two goals as guidelines, the Scheduling Office compares the test requests to the available resources and determines which tests are to be conducted each week.

B. LIMITING FACTORS

1. Schedule Structure

A weekly list of tests to be conducted, the master schedule, is generated on the Thursday before it becomes effective. Under normal conditions, all ranges are available for tests from 0700 to 1600 daily, except for the first Monday of each month. The morning of this day is set aside for maintenance and repair. The primary factor in scheduling tests is that a test range may only be used for one test at a time. The time required to conduct an individual test does not exceed nine hours, and tests are prohibited from starting on one day and finishing on another.

2. Resource Limitations

In addition to range restrictions, schedule creation is complicated by a variety of equipment, personnel, and logistic considerations.

First, the equipment required for tests is limited. Several major facilities, such as the Telemetry Control Center (T-PAD), are unique and therefore only one test requiring the T-PAD can be run at any given time.

The second major constraint is availability of personnel. Camera operators, target builders, and radar operators, to name a few, are trained specialists. There are not enough of these people to man all the ranges all the time.

There also exist two logistical problem. Sometimes, tests require a special camera that is in limited supply. This means that these cameras must be moved from site to site depending upon the test. To further complicate matters, the time required to transport and set up such a camera varies as a function of its current location and its destination. It can take as many as two days to move a camera and prepare it for a test. The other logistical issue is safety related. One type of test conducted at NWC is an air-to-air missile test. When such a test is being conducted, for reasons of safety, there can be no unrelated aircraft in the Center airspace. Thus, any other tests requiring aircraft are not permitted even though the resources are available for such tests.

Working within these constraints to achieve the above stated goals, the Scheduling Office prepares its weekly test plan.

C. SCOPE OF MODELING EFFORT

All of the nuances of scheduling cannot be completely integrated into an automated scheduling model. The problem of scheduling must be simplified and structured in a manner consistant with computer applications and limitations. The simplifiying assumptions are described below.

First, there are several ranges which are jointly managed by the Scheduling Office and other organizations, most notably the Electronic Warfare Test and Evaluation System (EWTES) Facility. These are truly national assets and are dominated by decisions made outside the Naval Weapons Center. For the purposes of this model, the tests requiring these facilities are scheduled as a separate process.

The scheduling system in this thesis deals with twenty-five of the Center's many ranges. Table 1 is a list of the included ranges and air space. R2508 corresponds to the total airspace of the Center. Certain tests, such as air-to-air missile shots, require that aircraft necessary for that test be the only aircraft flying in the region. Use of R2508 precludes any tests requiring flying aircraft center-wide.

TABLE 1. CENTER RANGE FACILITIES

1. T11 Gun Range	14. Naval Airfield
2. G-2 Range	15. Cactus Flat
3. G-4 Track	16. Target Airfield
4. G-9 Range	17. Parachute Range
5. Airport Lake	18. Redeye
6. Baker Range	19. SNORT Range
7. Charlie Range	20. Randsburg Wash
8. Darwin Wash	21. X-Pad
9. Coles Flat	22. K-2 Range
10. Golf Range	23. G-6 Range
11. Coso Range	24. R-2506 Airspace
12. Mirror Lake	25. R-2508 Airspace
13. MJB 2 Range	

Equipment and facility constraints are more complicated to describe. The availability of each type of equipment can vary from week to week or even hour to hour, depending on failures, repairs, and scheduled down time for maintenance. The values presented in Table 2. are estimates established for the development of the scheduling system. It should be noted that the M-45 cameras mentioned here are of the special type which are moved as needed. There are other cameras permanently stationed at each range. It is assumed that when a range is used these cameras are available for use as well.

Available staff for conducting tests, in all likelihood, will vary within a week. Also, test personnel have varying levels of proficiency in operating the various types of equipment required during a test. Again, to facilitate the implementation of the model and to simplify the computer modeling, it is assumed that personnel availability remains constant throughout the week and it is assumed that all personnel are equally competent within a given category. For example, all camera operators can operate any camera with equal proficiency. Table 3 contains the personnel types and the number of individuals available.

TABLE 2. EQUIPMENT

Equipment	Number Available
1. Askania Cameras	4
2. Bowen Cameras	5
3. Computer Channels	3
4. Fixed Video Cameras	17
5. Special Communication Link	1
6. Mobile Frequency Monitors	2
7. Laser Trackers	3
8. Laser Vans	1
9. M-45 Cameras	6
10. Generators	10
11. Drone Controls	2
12. Radar #1	1
13. Radar #2	1
14. Radar #3	1
15. Radar #4	1
16. Telemetry Pad	1
17. Mobile Telemetry Van	1
18. Video Scoring Equipment	10
19. Video Recording w/Radar	8
20. Radio Frequency Targets	6
21. Moving Target Controls	1
22. Fixed 16mm Cameras	20

TABLE 3. PERSONNEL

Personnel	Number Available
1. Camera Operators	25
2. Target Support Personnel	5
3. Laser Safety Officer	2
4. Drone Pilots	2
5. Radar Crews	4
6. Air Range Controllers	7
7. Ground Range Controllers	4
8. Ground Support Personnes	7
9. Explosive Ordnance Disposal	5
10. Moving Targe Drivers	2

The candidate tests vieing for range time are described by a variety of parameters and resource requirements. Among these are the times required to prepare for the test, to conduct the test, and to clean up after the test. In some cases, it might be possible to set up for a test several hours prior to the time it is to be conducted. Along the same lines, there are times when clean up will occur some time after the test has been completed.

These possibilites were not considered here. "Contiguous schedules" were the only schedules considered. That is, the test time associated with each test includes preparation time, clean-up time, and run time of the test, and all three segments of a test must occur on the same day in contiguous blocks of time.

III. MODEL DEVELOPMENT

A. THE MODEL

The model for this problem, similiar to others which use set partitioning approaches, is based upon the generation of all possible schedules for each test, followed by the selection of an optimal set of schedules from among those candidates.

The objective is to maximize the sum of the priorities of the tests being scheduled during a one week period. This must be accomplished subject to several constraints. First, any test may be scheduled at most once, and if there is a mandate to conduct that test during the week, the test must be scheduled once. Second, the quantity of resources required by all tests being conducted simultaneously must be less than the quantity of those resources available at that time. Third, if a test is conducted involving an air-to-air missile firing, no other tests involving aircraft will be conducted at the same time. Fourth, movable specialty cameras requested for tests will be available for those tests. To handle this last constraint it is also necessary to generate all the possible movement schedules for each camera and to select a feasible set of camera schedules as well.

B. INITIAL MODEL FORMULATION

1. Indices:

i - test

j - candidate test schedule

k - resource type

t - time period

c - specialty camera

l - candidate camera schedule

J^i - the set of candidate test schedules associated with test i

J^s - the subset of all schedules associated with tests involving an air-to-air missile launch, and therefore requiring exclusive use of airspace

J^k - the subset of all schedules associated with tests involving airborne assets but not air-to-air missile shots.

J^c - the subset of all schedules associated with tests that require the use of movable special cameras c

L^c - the set of all candidate camera schedules associated with camera c

L^j - the set of all candidate camera schedules which can be used to satisfy camera requirements for test schedule j

2. Data

The data are of two types: test parameters and requirements, and resource availability constraints. They are:

P_i - priority of test i

A_{kjt} - the amount of resource k required for test schedule j in time period t

M_j - number of cameras required by candidate test test schedule j

R_{kt} - amount of resource k available in time period t

$$D_i = \begin{cases} 1 \text{ if test i must be run this week} \\ 0 \text{ otherwise} \end{cases}$$

For $j \in J^s$

$$B_{jt} = \begin{cases} 1 \text{ if airspace is required for test schedule j} \\ \quad \text{in period t} \\ 0 \text{ otherwise} \end{cases}$$

For $j \in J^k$

$$E_{jt} = \begin{cases} 1 \text{ if test j requires aircraft to be flying} \\ \quad \text{during period t} \\ 0 \text{ otherwise} \end{cases}$$

3. Decision Variables

The decision variables relate to the choice of either selecting or not selecting a candidate test schedule to be part of the weekly master schedule and to the choice of either selecting or not selecting a candidate camera schedule to insure proper placement of specialty cameras during the week.

$$X_j = \begin{cases} 1 \text{ if candidate test schedule } j \text{ is chosen} \\ 0 \text{ otherwise} \end{cases}$$

$$Y_l = \begin{cases} 1 \text{ if candidate camera schedule } l \text{ is selected} \\ 0 \text{ otherwise} \end{cases}$$

4. Formulation

The formulation can be described mathematically as follows:

$$\text{Maximize} \sum_{i} \sum_{j \in J^i} P_i \, X_j$$

Subject to:

$$D_i \leq \sum_{j \in J^i} X_j \leq 1 \quad \text{for all } i \qquad (1)$$

$$\sum_{j} A_{kjt} \, X_j \leq R_{kt} \quad \begin{array}{l}\text{for all } t \\ \text{for each } k\end{array} \qquad (2)$$

$$\sum_{j \in J^s} B_{jt} \, X_j + \sum_{j \in J^k} E_{jt} \, X_j \leq 1 \quad \text{for all } t \qquad (3)$$

$$\sum_{l \in L^c} Y_l \leq 1 \quad \text{for all } c \tag{4}$$

$$M_j X_j - \sum_{l \in L^j} Y_l \leq 0 \quad \text{for each } j \in J^c \tag{5}$$

C. EXPLANATION OF FORMULATION

There are two sets of decision variables for this model. The first set comprise booleans, X_j, associated with the list of candidate test schedules which define a span of time periods during which test j might be successfully conducted. If candidate schedule j is chosen to be part of the master schedule, then X_j is assigned a value of 1. If not, X_j takes the value of 0. The second decision variable, Y_l, is also a boolean. Each of these is related to a candidate movement schedule for each specialty camera. As with the X_js, if a movement schedule for a specialty camera is selected, then that Y_l value takes on a value of 1. If not, it is assigned a value of zero. The objective function and the constraints are explained in detail below.

1. Objective Function

The objective function of this model is to maximize the sum of the priorities of the tests being scheduled. The actual priority values can be set to any reasonable values.

Priorities of high=3, medium=2, and low=1 were used in this analysis.

2. Constraints

Figure 1. illustrates the basic structure of the first two constraint sets within the A matrix. This example presents a simplified version of the test-scheduling problem formulation. There are three tests, two ranges and two resource types, and each day consists of nine time periods.

Equation (1) defines constraints which state that each test i may be scheduled at most once, and in certain cases, i.e., when $D_i = 1$, the test must be scheduled during the week. (In fact, when $D_i = 1$ the test must be scheduled during a specified day during the week.) These are "schedule selection constraints" which typically appear in set packing, covering and partitioning models, e.g., Brown, Graves, and Ronen [Ref. 1], and Marsten, Mueller, and Killion [6]. The configuration of these constraints can be seen in the first partition of the matrix shown in Figure 1.

The constraints described by Equation (2) require that the available resources such as ranges and personnel not be exceeded. For each resource type k, the amounts required by all test scheduled during the same time period cannot be greater than the quantity available during that time period. As can be seen in Figure 1, the nonzero

		Candidate Test Schedules																
		X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	
	1	1	1	1	1	1												≤ 1
	2						1	1	1	1	1							≤ 1
	3											1	1	1	1	1	1	≤ 1
	1	1										1						≤ 1
R	2	1	1									1	1					≤ 1
A	3		1	1								1	1	1				≤ 1
N	4			1	1							1	1	1	1			≤ 1
G	5				1	1							1	1	1	1		≤ 1
E	6					1								1	1	1	1	≤ 1
	7														1	1	1	≤ 1
1	8															1	1	≤ 1
	9																1	≤ 1
	1	1					1											≤ 1
R	2	1	1				1	1										≤ 1
A	3		1	1			1	1	1									≤ 1
N	4			1	1			1	1	1								≤ 1
G	5				1	1			1	1	1							≤ 1
E	6					1				1	1							≤ 1
	7										1							≤ 1
2	8																	
	9																	
	1	2					4											≤ 6
R	2	2	2				4	4										≤ 6
E	3		2	2			4	4	4									≤ 6
S	4			2	2			4	4	4								≤ 6
	5				2	2			4	4	4							≤ 6
1	6					2				4	4							≤ 6
	7										4							≤ 6
	8																	
	9																	
	1	3					2					5						≤ 10
R	2	3	3				2	2				5	5					≤ 10
E	3		3	3			2	2	2			5	5	5				≤ 10
S	4			3	3			2	2	2		5	5	5	5			≤ 10
	5				3	3			2	2	2		5	5	5	5		≤ 10
2	6					3				2	2			5	5	5	5	≤ 10
	7										2				5	5	5	≤ 10
	8															5	5	≤ 10
	9																5	≤ 10

Figure 1. Example of Matrix Formulation

elements in each column will occur in contiguous positions since a test uses resources in contiguous time blocks. If the amount of resource k required by a test is 1, as is the case when k refers to a range, then the set of constraints over t for that k will have the "contiguous ones" property which frequently arises in scheduling models (see Bartholdi, Orlin, and Ratliff [Refs. 3,4] and Bartholdi [Ref. 6]). A constraint matrix with this property also exhibits total unimodularity which leads to integer solutions. Unfortunately, only a portion of the constraints defined by Equation (2) have contiguous ones. The remainder are more general, consisting of sets of constraints having contiguous nonzero elements which can range from 1 to the low 20s. (Even if all matrix entries were 1s, the fact that there are multiple sets of contiguous ones would also allow the possibility of noninteger solutions.) Examples of these sets of constraints can be found in the last two partitions of the matrix presented in Figure 1. (Note that the t^{th} constraint for range 2 makes the t^{th} constraint for resource 1 redundant allowing its elimination. However, for the full-scale problem it is unlikely that such situations will occur. Thus, this redundancy is not worth attempting to exploit.)

Equation (3) insures that when an air-to-air missile test is being conducted, only those aircraft directly associated with the test are in the NWC airspace.

Equation (4) is to the candidate camera schedules what Equation (1) is to the candidate test schedules. It states that one, and only one, candidate schedule for each camera will be selected.

The formulation of Equation (5) is designed to insure that the chosen candidate test schedules overlap with the chosen candidate camera schedules such that the proper number of cameras will be located on the specified ranges when a test using those ranges is conducted. It should be noted here that a schedule, l, cannot satisfy more that one camera requirement in any time t. This is because each camera movement schedule places at most one camera on one range at any time t, and there is at most one test per range at any time t. One important aspect of scheduling these specialty cameras is that a camera cannot be moved during a test. Through the selection criteria of eligible camera schedules, L^j, Equation (5) also insures that the cameras will remain in place during the entire duration of the test. A formulation which simply dealt with these cameras as resource constraints would allow situations where camera coverage of a test could be met by having one camera at the range for the first part of the test and then having another

camera covering the requirement during the remainder of the test while the first was moved to another range. This is not realistic. A camera allocated to a test must be allocated for the entire duration of the test.

In the above formulation, the matrix with elements A_{kjt} represents a list of all possible test schedules. Analogoulsy, there should be another matrix representing a list of all possible camera movement schedules. However, through the use of the index set L^j, the latter matrix becomes unnecessary and can be eliminated, thereby decreasing the number of constraints in the problem. Although the camera schedules need not be explicitly represented, they must still be generated in order to determine the set L^j prior to the generation of inputs to the solver.

IV. IMPLEMENTATION

The implementation of this model requires gathering data on the type of tests usually conducted at NWC, the resource requirements typical of those tests, and the availability of resources and ranges during a typical week. A solver must also be selected and a program must be developed to generate the inputs for that solver. Integral to this program is the generation of all the possible test schedules and camera placement schedules. Lastly, implementation must include transformation of the solver output into the weekly master schedule.

A. DATA COLLECTION

The data required to solve the test-scheduling problem falls into two categories: test and resource availability data. Test data consists of information on resource needs, time and range requirements, priority, duration, earliest begin time, latest begin time, and other information. Resource availability data is made up of values reflecting how much of each resource is available during each time period within the week.

A sample of fifty test requests was used to demonstrate the solution techniques described below. Thirty-eight of these requests were actual test requests obtained from the

Scheduling Office of the Naval Weapons Center. The other twelve were obtained by modifying some of the first test requests.

The data for these fifty test requests was placed in a single computer file labeled TEST DATA. The information about each test occupies four lines. The first line contains test parameter data such as priority and test duration. The remaining lines list the quantity of resources required by the test. Appendix A contains a description of the data format.

Resource availability was collected through interviews with NWC Personnel. The Scheduling Office provided most of the data, with the Electro-Optical Branch furnishing information on the availability of cameras and camera operators. It was assumed for the purpose of this thesis that resource availability would be constant throughout the week. This data was placed in the Resource Availability data file. The format of this data file is similiar to the format of the test data. It is also contained in Appendix A.

B. INTEGER PROGRAMMING SOLVER

The X-System [Ref. 7], a primal / dual linear programming solver with integer programming and nonlinear programming capabilities, was selected as the solver to be

used for this test-scheduling problem. It was chosen because of its success in solving similar problems [Refs. 8,9].

C. SOLUTION METHODS

The solution to the complete test-scheduling problem requires that all the candidate test schedules and the candidate camera movement schedules be generated and be assigned decision variables. Prior to the programming effort, a few calculations were conducted to get a rough idea as to the size of the problem as formulated. With fifty tests as inputs into the model, each one averaging about three hours, it was estimated that there would be approximately 1750 candidate test schedules, i.e., 1750 X-variables in the A matrix. Added to this are the unknown number of Y-variables associated with the candidate camera movement schedules. The number of rows was estimated to be large as well. Constraint (1) results in 25 rows. The assumption of nine hours in a day and hence 45 time periods in a week, combined with fifty-four different resources means that Constraint (2) contributes in excess of 2400 rows. This results in a large integer programming problem regardless of the number of rows generated by Constraints (3), (4), and (5) and the number of camera schedules. In fact, eliminating constraints (4) and (5) and the variables Y_1, a shortened formulation was still beyond the

computational capabilities of the X-System. Thus, an alternative is needed.

One such option is the use of a stepwise optimization in a iterative fashion. The basic structure would be as follows. First, using Constraints (1), (2), and (3) obtain an initial optimal solution independent of the camera movement constraints. Second, compare this solution set of test schedules to the set candidate camera movement schedules. If there exists a set of candidate camera movement schedules which meet the needs of the selected test schedule, then the optimal solution has been determined. If not, an additional constraint is added to the formulation as a third step. This constraint eliminates the initial optimal set of test schedules from the set of feasible solutions of future optimizations. This constraint has the following form:

$$\sum_{j \in J^m \cap J^c} X_j \leq C(J^m \cap J^c) - 1 \qquad (6)$$

where: J^m - set of test schedules selected by the optimizer during iteration m

J^c - the subset of all schedules associated with tests that require the use of moveable special cameras

C(*) - Cardinality function, generates the cardinality of *

With a new constraint, the enlarged problem is solved in order to select another set of test schedules and the process is repeated until a set of test schedules, for which there is a set of feasable camera schedules, is found.

A second option is to ignore the camera movement schedules and constraints altogether, solve the optimization without them, and then have the schedulers determine, off line, if the chosen set of test schedules is compatable with camera movements. If so, fine. If not, the schedulers can do several things to achieve a feasible set of test schedules: (i) make some changes by hand to the optimizer's selection of test schedules; (ii) eliminate a specific schedule j or test i (and, hence, all of its candidate schedules) from the set of candidate schedules and run the optimizer again; or (iii) add a constraint (such as Constraint (6)) that eliminates the chosen set of test schedules from the original set, and run the optimizer again.

For the purpose of this thesis, the second alternative was considered. The generation of all candidate camera movement schedules is difficult given the large number of potential schedules. Each of the six cameras can be moved several times a day to any one of twenty four different ranges. The schedulers at NWC believe that they can deal with the camera movement issue off line [Ref. 10]. In

summary, the model under consideration consists of Equations (1), (2), and (3) and only variables X_j.

D. GENERATING SCHEDULES

The candidate test schedules for each of the tests are critical inputs. These were generated within a FORTRAN program that transformed the test and resource data files into the constraint equations. The program was constructed in such a manner as to generate only the feasible candidate schedules. No candidate schedule was created that crossed days, nor was a candidate schedule for a test generated that had a start time before the earliest begin time or after the latest begin time associated with that test. Simultaneously with the generation of the candidate schedules, a data file tying each candidate schedule with a test and a start time is created. This file, the Schedule Listing, is used to generate the master schedule from the output file generated by the X-System.

E. ADDITIONAL SIMPLIFICATION

After the relaxation of the camera constraints, the resulting problem was still too large for the X-System. To alleviate this difficulty, the original problem designed to schedule tests for one week at a time was partitioned into five daily scheduling problems. To obtain a week schedule, these five problems were solved in sequence and the

available resources were updated after each day to reflect the remaining amount. One advantage in solving the problem in this manner is that high priority tests tend to be scheduled early in the week. However, it should be noted that the resulting solution is not necessarily optimal.

F. OBTAINING THE MASTER SCHEDULE

The actual output of the X-system is the optimal value of each of the X_j's. A FORTRAN program was written to convert this output into a more useable form called the master schedule. The program requires as input the output from the X-System and the Scheduling listing. An example of the completed master schedule is given in Figure 2.

```
SCHEDULE FOR MONDAY
Test 9  runs 7  hundred to 9  hundred
Test 11 runs 7  hundred to 9  hundred
Test 15 runs 7  hundred to 9  hundred
Test 27 runs 7  hundred to 9  hundred
Test 49 runs 7  hundred to 9  hundred
Test 2  runs 7  hundred to 10 hundred
Test 28 runs 9  hundred to 10 hundred
Test 46 runs 9  hundred to 10 hundred
Test 32 runs 9  hundred to 11 hundred
Test 39 runs 9  hundred to 11 hundred
Test 26 runs 9  hundred to 12 hundred
Test 3  runs 10 hundred to 12 hundred
Test 12 runs 13 hundred to 15 hundred
Test 31 runs 13 hundred to 15 hundred
Test 29 runs 13 hundred to 15 hundred
Test 50 runs 14 hundred to 16 hundred
Test 25 runs 15 hundred to 16 hundred
SCHEDULE FOR TUESDAY
Test 35 runs  7 hundred to 10 hundred
Test 43 runs  7 hundred to 10 hundred
Test 13 runs 10 hundred to 13 hundred
Test 44 runs 10 hundred to 13 hundred
Test 18 runs 13 hundred to 16 hundred
Test 40 runs 13 hundred to 16 hundred
Test  1 runs 14 hundred to 16 hundred
SCHEDULE FOR WEDNESDAY
Test 34 runs  7 hundred to  9 hundred
Test  5 runs 10 hundred to 12 hundred
Test 10 runs 11 hundred to 13 hundred
Test 23 runs 12 hundred to 14 hundred
Test 45 runs 14 hundred to 16 hundred
SCHEDULE FOR THURSDAY
Test 17 runs  7 hundred to  9 hundred
Test 30 runs  7 hundred to 10 hundred
Test 36 runs  9 hundred to 11 hundred
Test 42 runs 11 hundred to 13 hundred
Test 22 runs 13 hundred to 16 hundred
SCHEDULE FOR FRIDAY
Test 14 runs  7 hundred to 10 hundred
Test 47 runs  7 hundred to 10 hundred
Test 37 runs 10 hundred to 13 hundred
Test 20 runs 13 hundred to 16 hundred
```

Figure 2. Example of Master Schedule

V. RESULTS AND CONCLUSIONS

A. RESULTS

The test scheduling problem, without the special camera constraints, was approximately solved by the X-System. Solution of the integer program resulted in an objective function value of 80.0. Out of the fifty test requests, thirty-eight were scheduled for the week, thirteen of which were high priority tests, sixteen medium priority, and nine low priority. The master schedule in Figure 2 shows when each of the selected tests was scheduled to run.

The solver was set to stop execution when an integer solution within twenty percent of the optimal linear solution is found. With this criteria, the solver found the desired solution in about eight minutes and thirty-four seconds of CPU time.

B. CONCLUSIONS AND RECOMMENDATIONS

It has been demonstrated that scheduling tests on the NWC Ranges can be facilitated by the application of computer optimization techniques. Range personnel have seen the product described in the previous pages and feel that a slight modification of the existing model could be integrated into their scheduling efforts. Interestingly enough, the fact that the optimizer schedules one day at a

time is viewed as an advantage to the Scheduling Office. Addressing the scheduling problem one day at a time allows for the cancellation and addition of test requests which frequently occur during the week.

It has been suggested to the Scheduling Office that additional work be done to enable this test-scheduling process to be used at NWC. This will allow schedulers to validate the model by running it and comparing the results simultaneously with existing efforts.

There are other steps to be taken to make this system usable by NWC. First, a computer link must be established between NWC and NPS so that the X-System can be used. Second, a user-friendly front end must be developed to facilitate data entry. This should be done for both the test data and the resource availability data. Third, a batch program must be developed to not only automate the generation of the constraint matrix, but also to provide access to the X-System as well as to generate the weekly master schedule. This would enable schedulers to get results with a few keystrokes.

Additional work on the mathematical programming aspect of this problem would also be potentially useful. Using some advanced techniques as "problem cascades" (See Bausch [Ref. 11].) it may be possible to solve the full linear programming relaxation of the problem. Constraint

branching, as used in Ryan and Foster [Ref. 12], has helped in solving set partitioning and covering problems and could be useful here. Methods to tighten the linear programming relaxation of the integer programming may be worthwhile, too.

APPENDIX A

TEST DATA FORMAT:

The following is a record for a single test:

```
1 1.5 1 1 45 0 1 0
0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 2 1 0 0 0 0
0 0 1 0 0 0 0 0 0 0 2 1 0 0 0 0 0 0
```

The first row contains, in order, the following test parameters:

1. Test I.D number
2. Test Duration (measured in half hour increments)
3. Priority
4. Earliest Begin Time Acceptable
5. Latest Begin Time Acceptable
6. 1 if test is required
   0 otherwise
7. 1 if test involves air-to-air missile
   0 otherwise
8. 1 if test involves aircraft but not air-to-air missile
   0 otherwise

The test duration values are rounded up to the next highest hour for the solution to the problem as formulated.

The second row contains 0/1 indicators for each of the 25 ranges available for testing. If a range is required, the value of the data entry is 1; it is 0 otherwise. Table

A1 lists the range name and its corresponding location in the data file.

TABLE A1. CENTER RANGE FACILITIES

1. T11 Gun Range	14. Naval Airfield
2. G-2 Range	15. Cactus Flat
3. G-4 Track	16. Target Airfield
4. G-9 Range	17. Parachute Range
5. Airport Lake	18. Redeye
6. Baker Range	19. SNORT Range
7. Charlie Range	20. Randsburg Wash
8. Darwin Wash	21. X-Pad
9. Coles Flat	22. K-2 Range
10. Golf Range	23. G-6 Range
11. Coso Range	24. R-2506 Airspace
12. Mirror Lake	25. R-2508 Airspace
13. MJB 2 Range	

The third row lists the number of each type of personnel required for the test. Table A2 contains a list of the personnel types and their positions in the data field.

The fourth row lists the number of each type of equipment required for the test. Table A3 contains a list

of the equipment types and their positions in the data field.

RESOURCE AVAILABILITY DATA FORMAT:

```
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
25 5 2 2 4 7 4 7 5 2
4 5 3 17 1 2 3 1 6 10 2 1 1 1 1 1 1 10 8 6 1 20
```

The first row is range availability. The value 1 indicates that only one test can use a range during a time period.

Rows 2 and 3 contain the numbers of personel and equipment available during each time period. Tables A2 and A3 relate position of the data in the data fields to the types of personnel and equipment.

TABLE A2. PERSONNEL

Personnel	Number Available
1. Camera Operators	25
2. Target Support Personnel	5
3. Laser Safety Officer	2
4. Drone Pilots	2
5. Radar Crews	4
6. Air Range Controllers	7
7. Ground Range Controllers	4
8. Ground Support Personnes	7
9. Explosive Ordnance Disposal	5
10. Moving Targe Drivers	2

TABLE A3. PERSONNEL

Personnel	Number Available
1. Camera Operators	25
2. Target Support Personnel	5
3. Laser Safety Officer	2
4. Drone Pilots	2
5. Radar Crews	4
6. Air Range Controllers	7
7. Ground Range Controllers	4
8. Ground Support Personnes	7
9. Explosive Ordnance Disposal	5
10. Moving Targe Drivers	2

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